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DEVELOPMENT OF AN ON-LINE STRESS/VIBRATION MEASUREMENT CAPABILITY FOR STEAM GENERATOR TUBES

Report No. 87-111-K

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ABSTRACT

This report documents a comprehensive laboratory program which involved the development of a measurement system for the on-line investigation of stress/vibration degradation mechanisms in steam generator tubes. Past Bruce NGS steam generator tube failures, postulated as due to low amplitude/high cycle fatigue, have prompted the development of this on-line measurement capability so that it will be available to investigate possible future problems of this nature.

Documented in this report are the results of three interrelated investigations which demonstrated that in situ strain gauge measurements would be practical, safe and effective for obtaining valuable information on the structural behavior of steam generator tubes during all phases of reactor operation.

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EXECUTIVE SUMMARY

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STRESS/VIBRATION MEASUREMENT
CAPABILITY FOR STEAM GENERATOR TUBES

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The development and documentation of an on-line capability to measure stress and vibration on operating steam generator tubes is the subject of this report. This capability is required to be in place to readily investigate the causes of possible future steam generator tube degradation and failures. From the analysis of a series of past tube failures at Bruce NGS A, which have not continued, low amplitude/high cycle fatigue has been implicated as the failure mechanism. This study was a result of a concern that additional tube failures would occur. It involved comprehensive laboratory investigations which resulted in:

1. A determination that in situ steam generator tube stress and vibration measurements based upon strain gauges would be capable of detecting and characterizing various failure and degradation mechanisms; and
2. Documented test results which demonstrated that on-line strain gauge measurements would be practical to perform on operating steam generators and would likely not adversely affect tube integrity.

A small proof of concept trial installation on operating steam generator tubes was initially considered to be the final step in this program in order to detect and correct possible deficiencies in our approaches (which are unable to be foreseen or readily checked out in the laboratory). There are no plans at this time to implement these verification measurements.



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To Mr. R.J. Strickert
Manager, CNS
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DEVELOPMENT OF AN ON-LINE
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CAPABILITY FOR STEAM GENERATOR TUBES

1.0 INTRODUCTION

Steam generator tube reliability is of paramount importance for the efficient operation of Ontario Hydro nuclear stations. In the past, a small number of tube failures at Bruce NGSA had occurred which required unplanned unit shutdowns. These shutdowns were expensive in terms of the repairs themselves and particularly in terms of the cost of replacement power. Although these past tube failures may have been isolated occurrences and may not indicate a deterioration in the future reliability of the remaining tubes, there remains the possibility that significant numbers of failures may occur in the years to come. As such, there is a need to have a comprehensive capability that is readily available to investigate the causes of such failures, in order to effect expedient and appropriate action.¹

Possible causes of future steam generator tube failures may be due to certain stress related phenomena which would be manifested only during unit operation. (The cause of the past tube failures at Bruce NGS A was tentatively identified as low amplitude/high cycle fatigue.) As such, a request (to Mechanical Research Department from the BNGS 'A' Steam Generator Tube Steering Committee) was made to develop the necessary in situ measurement capability so that it would be able to perform future investigations when required. Specifically a project was undertaken to develop and prove out an on-line stress/vibration measurement capability for future investigations of steam generator tube behaviour during all phases of unit operation.

¹ "Proposed Approach to Investigate Stress-Related Mechanism in Stress Generator Tube Failures," M.T. Flaman, Report No 83-228-K. June 20, 1983.

This report documents the laboratory studies that were required to develop the necessary stress/vibration measurement capability and to demonstrate that it would be practical, safe and effective to perform on-line measurement investigations on operating steam generator tubes.

The initial plan for the development of this capability involved extensive laboratory studies which were to be followed by a small proof of concept study on an operating steam generator. This report discusses and documents the results of the laboratory studies.

2.0 SUMMARY

Failure or degradation mechanisms in steam generator tubes involve structural phenomena: tube leakage or bursting results when stress in the tube wall exceeds the stress capability of the tube material to contain internal pressure. Stress-related phenomena may be an indication or a consequence of other types of tube failure mechanisms or such stress-related phenomena may be the primary cause of failure.

As such, an important requirement to have available for Ontario Hydro steam generators is the capability of measuring the structural condition and behaviour of steam generator tubes.

Generally, the total tube stress magnitude may be categorized as being composed of three components:

- i) residual stress - due to tube fabrication and forming;
- ii) assembly stress - due to tube insertion into, and the resulting construction of, the steam generator; and
- iii) operating stress - due to unit operation.

The operating stress component may be further divided as: mean or quasi-static stress changes (arising as a result of temperature or pressure changes due to unit start up); and dynamic stresses (due to vibration during any phase of unit operation). (Note that "permanent" stress changes due to past unit operation, such as might have resulted in metal yielding, are not addressed in this report).

This report covers the development of an approach to measure in situ operating stresses on steam generator tubes. Specifically, the outside surfaces of accessible areas of tubes at the U-bend region of Bruce NGS 'A' steam generators were investigated for possible future measurement requirements utilizing strain gauges. (This is the area where past tube failures have occurred). Generally, the results of this study are:

i) Quasi-Static Stress/Strain Measurements

On-line quasi-static or mean stress/strain measurements will be able to be performed on steam generator tubes for extended periods of time (several years or longer). Accuracy of measurements would be sufficient to detect and quantify any significant mean stress degradation mechanism (such as possible tube lockup in a support sheet, etc).

ii) Dynamic Stress/Strain Measurement

Dynamic stress/strain measurements will be able to be performed at any expected vibrational frequency on operating steam generator tubes. Durations of measurement capability would be sufficient to obtain valuable information regarding frequencies and amplitudes for any significant vibration environment and would extend for a period to at least several weeks (for severe vibration) to several years (for low amplitude vibration).

iii) Investigation of Possible Relationship Between Vibrational Strain and Displacement

It was found to be not possible to infer mid-span tube displacements by performing strain measurements at the support locations. This would have been a desirable capability in order to increase the usefulness of each strain gauge.

But, because of fundamental non-linearities in the tube support system itself, the data from each strain gauge can be directly related only to the stress or vibration at the specific location of each gauge. That is, strain measurements at one location on the tube cannot necessarily determine strains at a remote location on the tube.

This is not a major problem because the choice of gauge location on the tube would not be made blindly but would be made on the basis of a knowledge of future failure locations and on a careful analysis of the postulated failure mechanism. In addition, several gauges could easily be located along the length of tube subspans in order to more effectively characterize tube behaviour.

On the basis of past tube failures, strain gauges would be located on accessible locations near the tube supports and at the mid points of tube subspans. Axial gauges would be located on the tube extrados and on the sides of the tubes in the uppermost tube subspans and, if possible, in the adjacent tube subspans, just above the top horizontal supports.

iv) Effect of Strain Gauging on Tube Integrity

The presence of the strain gauge which would be spot welded to the tube has raised a concern regarding the effect on the serviceability of the tube. (NRC, AECB and MCCR have given virtual blanket approval for the use of this procedure on nuclear pressure vessels at up to ten times the energy levels used in this application.)

Recent information, which relates to the spot-welding attachment procedure itself, indicates that no adverse effects would likely occur.²

In addition, fatigue tests on strain gauged tube sections indicated that tube integrity would not likely be reduced for a period of at least two years due to gauge attachment.

(It might be noted that a spin-off development of this study was the special design and fabrication of an advanced steam generator tube fatigue testing machine. It is able to perform any type of tests on integral tube sections of about 2 m in length at over ten million cycles per day. Temperatures at up to 300°C, with internal (primary) pressures and external (secondary) steam conditions can be accommodated). This capability is mentioned because of the potential usefulness of a steam generator tube fatigue testing facility for future requirements.)

The results of all the investigations are discussed in more detail, including photographs, in the next section. There will be no loss of continuity in this report by proceeding directly to Section 5.0 - Recommendations.

3.0 DESCRIPTION OF LABORATORY INVESTIGATIONS

Interrelated studies to develop an effective steam generator tube stress/vibration measurement system were carried out in three separate laboratories and can be categorized in three separate areas. The results of each of these investigations are summarized in this section.

3.1 Development of Accurate Calibration Procedures For Quasi-static Stress/Strain Measurements

The sensor selected for this application is the Eaton spot Weldable Resistance Strain Gauge as shown (attached to a steam generator tube section) in Figure 1 on the next page.

² "Information Related to Welding on Steam Generator Tubes", Memo to W.G. Babe from W.H.S. Lawson, April 16, 1987, File 823.42(t).

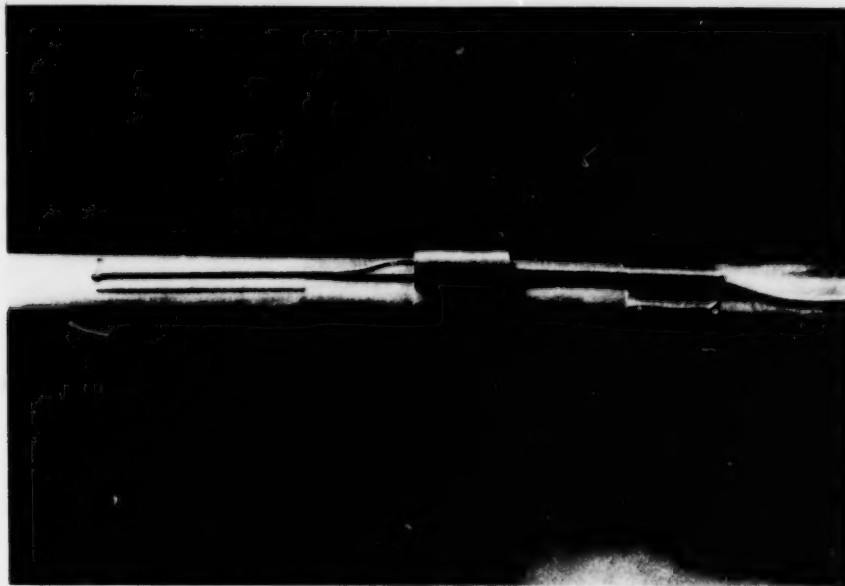


FIGURE 1
VIEW OF ATTACHED STRAIN GAUGE ON
STEAM GENERATOR TUBE

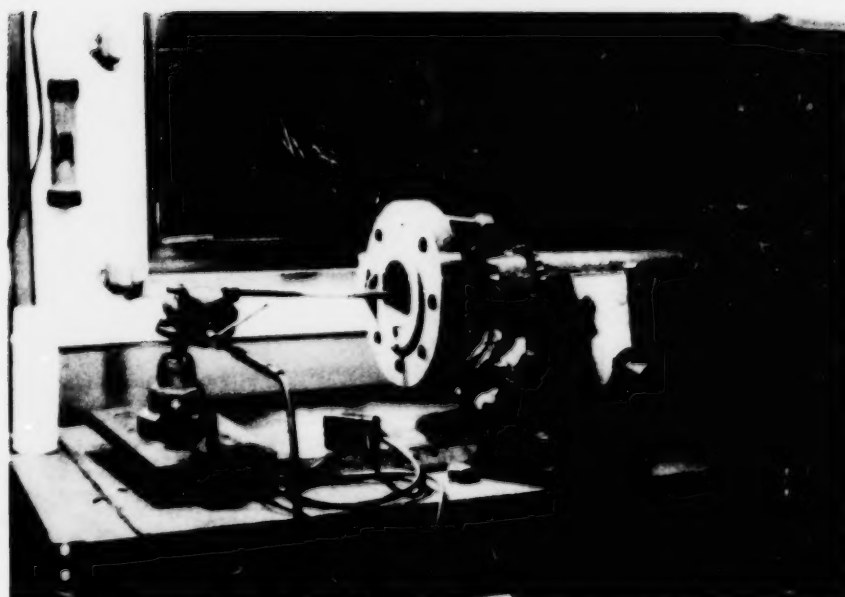


FIGURE 2
LABORATORY PRESSURE VESSEL AND
OVEN FOR STRAIN GAUGE TESTS

It is: light in weight; able to be attached directly to the outside surfaces of accessible tubes; able to be remotely monitored through long integral metal-sheathed lead wire; and is able to be used in environments of hot, pressurized steam for extended periods of time.

The general ability of this strain gauge approach to detect and quantify dynamic strain changes is well documented: it appears that accurate cyclic strain magnitudes and frequencies can readily be obtained from instrumented tubes under all conceivable steam generator conditions. As such, no specific laboratory studies were performed to generate additional information on the dynamic measurement characteristics of the strain gauge procedure. Therefore, there is a high degree of assurance that valuable information on dynamic strains and stresses will be able to be obtained and will enable the in situ fatigue behaviour of the tubes to be studied.

There exists an important concern regarding the quasi-static stress/strain changes on the steam generator tubes. Such quasi-static or mean stress changes would primarily occur during slowly varying changes in steam generator operating conditions, particularly during unit startup and shutdown occurrences.

Stress changes in the tubes due to pressurization and thermal effects (such as differential expansion between the hot and cold legs) would result in mean stress changes in the tubes. Other effects, such as might be due to possible tube lockup in the support plates, could result in large imposed stresses on the tubes.

Therefore, it would be important to detect and measure mean stress changes on the steam generator tubes in the event of future tube failures. There have been major problems in the past in obtaining accurate data on mean stress/strain changes from strain gauges where temperatures and pressures significantly change during the course of the measurements.

The ability to perform accurate mean or quasi-static stress/strain measurements depends on an ability to separate pressure and temperature effects on the strain gauge signal from actual stress-induced strain effects. These extraneous effects can be large, and because they are specific to each individual strain gauge a method to calibrate individual strain gauges in the laboratory before attachment to actual tubes was required. (It is not possible to perform an in situ calibration on the strain gauges.)

The experimental verification work was performed on actual steam generator tube sections which were tested in a small pressure vessel as shown in Figure 2. Temperatures and pressures, including primary/secondary water and steam conditions, duplicated the in-plant measurement environment.

This study involved the use of newly developed calibration clamps and the use of strain gauges especially made from Inconel 600 (the same material as the BNGS 'A' (and BNGS 'B') steam generator tubes). These two recent developments are significant and are critical to the ability to measure mean stress/strain changes on the steam generator tubes. As such, the Ontario Hydro capabilities in this area substantially exceed the general capabilities of only a few years ago.

The net results of this study are:

1. The gauges worked well, for extended periods of time (several months) under saturated steam conditions at 260°C with no failures. (No failure or deterioration was detected in the integrity of the tubes themselves at the gauge attachment locations over this time period).
2. Expected accuracies of quasi-static strain measurement would be about $\pm 70 \mu\epsilon$ (which can be related to a stress accuracy of approximately ± 2000 psi as compared to a yield stress of the tubes of about 50,000 psi).
3. Each gauge exhibits highly individual behavior requiring careful and time consuming calibration efforts. Quality control of the gauges by the manufacturer does not appear to be good. This requires extra laboratory effort and time to ensure reliability for each gauge.

Full details are contained in appendix A - "Calibration of Strain Gauges for Quasi-Static Stress Measurements".

3.2 Evaluation of the Use of Strain Gauges to Measure Tube Displacement Amplitudes and Frequencies

Substantial test efforts were performed to determine the suitability of using strain gauges to investigate displacement/vibration on operating steam generator tubes. A laboratory mock-up of the U-bend region of a steam generator tube was built (as shown in Figures 3 and 4) and enabled a number of exploratory tests to be carried out. Details are contained in Appendix B and results are discussed below.



FIGURE 3
BRUCE U-BEND TEST RIG

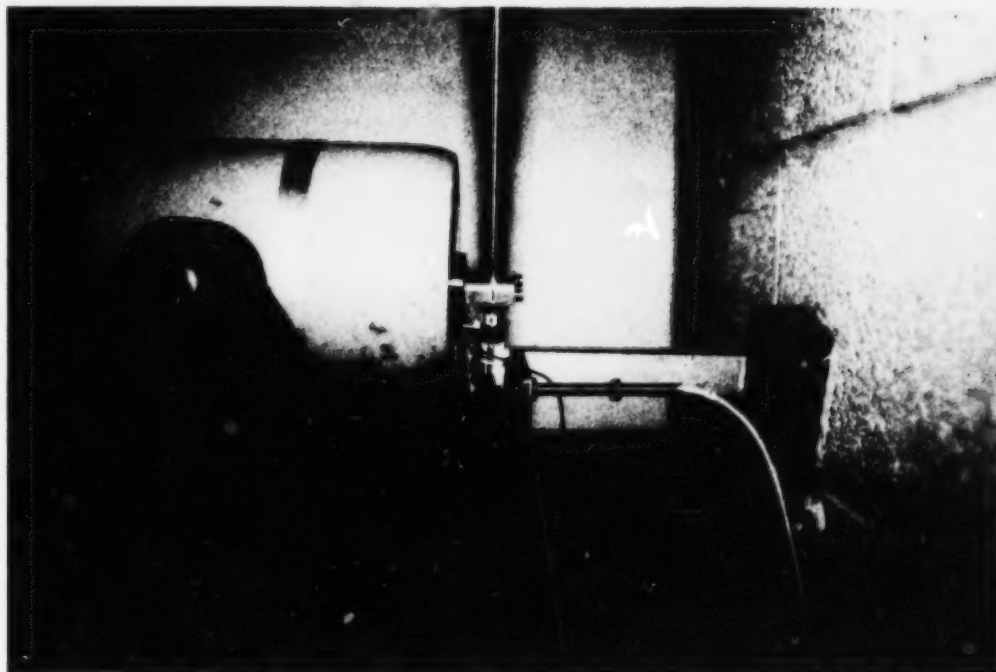


FIGURE 4
LING SHAKER & VIBRATION TRANSDUCERS AT
MIDSPAN EXCITATION LOCATION

The purpose of the tests was to determine whether or not a consistent relationship could be established between the dynamic strain (stress) measured at the support and the mid-span displacement. (It was not the intention of this program to test the use of strain gauges for dynamic strain measurement. The measurement of dynamic strain (stress) using strain gauges is a well-documented procedure which does not need to be re-established as discussed previously; however, the results described in this report do attest to the excellent dynamic response of strain gauges.)

Generally, the strain gauges provided consistently accurate information on the frequency response of the tube. However, no consistent relationship could be determined between the strain measured by a pair of gauges at a support and the corresponding mid-span displacement for the multi-span tube.

The basis for this occurrence are a number of factors such as the non-linear character of the tube/support interface and changes in the support conditions introduced by changes in the excitation level. Similar changes in support conditions would be introduced by thermal effects.

The discovery of the effect of changing support conditions on the strain has significant implications for the way in which the strain in the U-bend region is measured.

In order for the strain gauges to measure maximum in situ vibrational strains (stresses), they would have to be placed at the maximum strain locations on the tube. It was hoped that, from the vibration data, just one or two strain gauges could be used to indicate the maximum strains even if the gauges were located in another region of the tube. Unfortunately, this was found to be not true due to the factors discussed above.

This means that the precise attachment location of the gauges on the tube is important and must be judiciously made so that the chance of obtaining the peak stresses during the measurements will be increased. In addition, it might be prudent to instrument each measured tube at multiple locations in order to increase the likelihood of detecting maximum vibrational stress amplitudes.

As mentioned previously, the findings of this investigation do not present a major deficiency in the stress/vibration measurement capability. This is because much additional information will be available to assist in correctly choosing gauge locations on the tube, in the event that a future installation is required.

3.3 Investigation of Steam Generator Tube Structural Integrity Due to the Gauge Attachment Procedure (Fatigue Tests)

One of the major concerns involved in the instrumenting of steam generator tubes with strain gauges is the effect of the gauges on tube integrity. The effect, if any, of the strain gauges on the fatigue life of the steam generator tubes is the key issue. Any significant degradation of the structural integrity of the tubes due to the attachment of the strain gauges must be quantified beforehand as much as possible.

There are two main ways in which the gauges could adversely affect the life of steam generator tubes. The first is the geometric discontinuity created by the gauge, which may act as a stress concentration. The second way involves the introduction of the gauge spot welds which may cause tube failure due to stress/metallurgical effects.

Previous investigations in the US into the effects of weldable strain gauges on steam generator tube integrity have proven somewhat inconclusive but have generally indicated that no problems were apparent (see Appendix C). However, these results can only be directly applied to specific US steam generators and tubes: Ontario Hydro's steam generator tubes are generally of different geometry and/or material.

The major difficulty with previous investigations is the result of testing methodology. Both C-E and B&W used modified materials fatigue testing machines (four-point bending rotating beam machines) to fatigue test instrumented steam generator tubes. Results from B&W appeared to be inconclusive but were considered by them to be favourable³; results from C-E were possibly inapplicable because their tests were done on artificially wall-thinned tubes so that a standard test machine could be used.

The fatigue testing program described in this section and Appendix C was initiated in order to address these concerns.

The American society for Testing Materials (ASTM) has established uniform requirements for the fatigue testing of materials. These standard tests are not intended to determine the fatigue life of manufactured components, but to generate a baseline material fatigue curve for conservative design. There are many ways of

³ B&W did instrument the ID of steam generator tubes for Unit 2 at Three Mile Island nuclear plant with strain gages similar to the gages which we would use.

extrapolating the fatigue life of a steam generator tube from fatigue data on the material from which it is made, which are used in the design process. However, predicting the effect of gauge attachment on the fatigue life of the tubes is not possible given only material fatigue test data.

Therefore, it was decided that actual, unaltered steam generator tube samples must be tested, since the objective of the testing was to compare strain gauged tubes to a control group of ungauged tubes.

The choice of tube sample length to be tested was also quite important. In order to simulate in-plant conditions as closely as possible, it was decided to use a 69 in. long sample. This closely corresponds to the distance between support plates in Bruce NGS "A" steam generators.

Several alternative designs were considered for the fatigue testing machine. The final concept chosen was based on loading the tube as a pin-ended column and is shown in Figures 5 and 6. When the buckling load is reached, the tube deforms into a half-sine shape. Any desired stress amplitude can then be achieved by controlling the center point deflection of the tube. The loaded tube is then spun about its central (curved) axis to generate the alternating stress at a rate of 10,000,000 cycles per day. Details of the design of the test machine are found in Appendix C.

Since the tests are comparative, i.e. comparing the fatigue life of strain gauged tubes to non strain gauged tubes, the simplest test conditions were used initially in order to speed up development and testing. These conditions are room temperature and water filled (but depressurized) tubes. (The test machines have ovens included as part of their design, and tests at temperature and pressure similar to in service conditions can also be performed.)

The actual weldable strain gauges to be used in the field have been simulated by small pieces of Inconel 600 shim stock of the same size as the base flange of the strain gauges. These coupons of I600 are spot welded onto the tube the same way an actual gauge would be.

As of this writing, a sufficient number of tube samples have been tested to enable preliminary conclusions to be made. Each test takes, on average, 12 days to complete.

The results of the testing carried out so far indicate that the gauge attachment could have a shortening effect on the fatigue

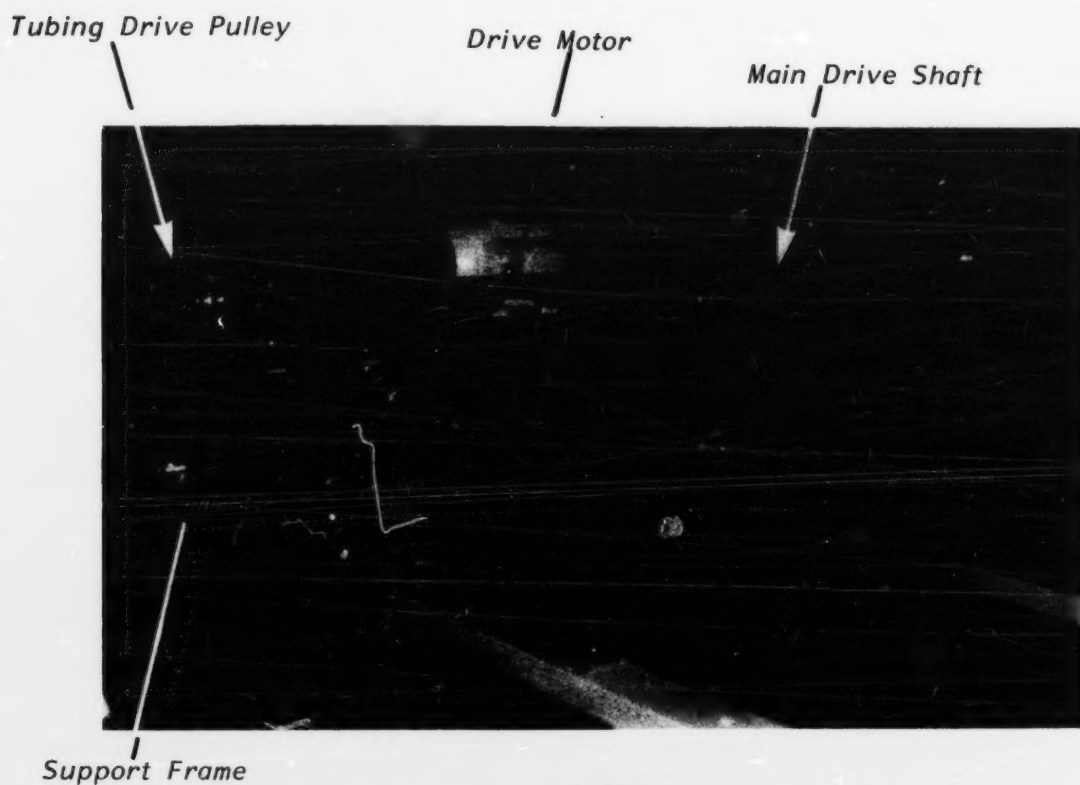


FIGURE 5
PROTOTYPE FATIGUE MACHINE

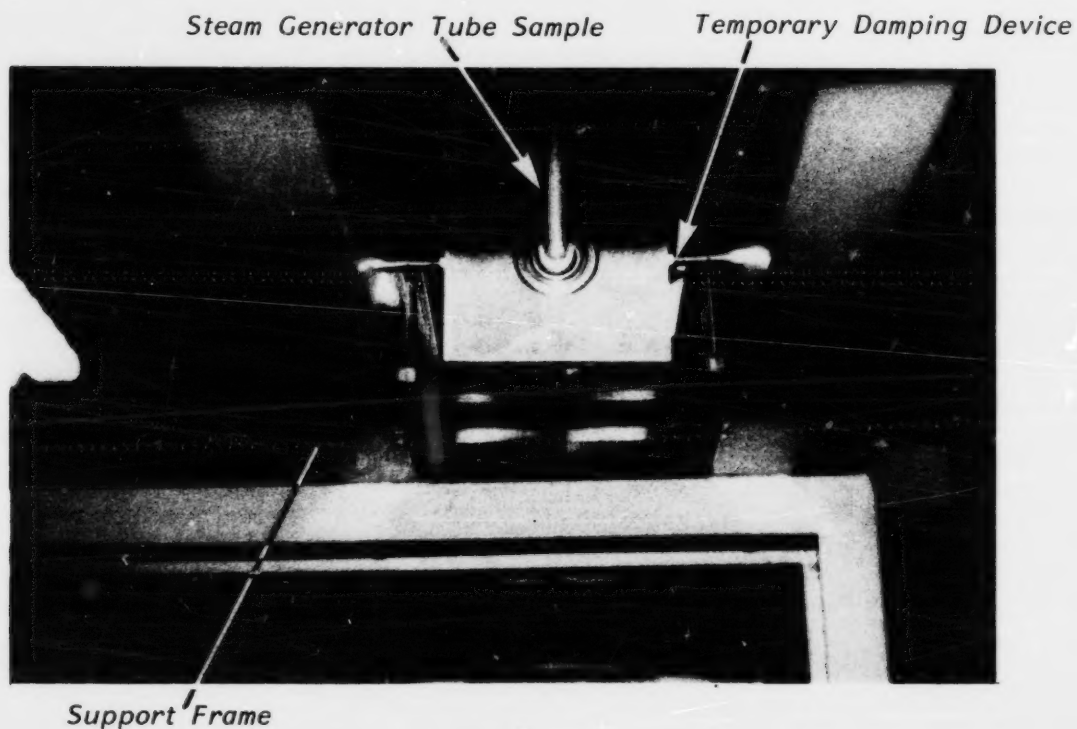


FIGURE 6
STEAM GENERATOR TUBE BEING
TESTED IN FATIGUE MACHINE
(BOTTOM VIEW)

life of the steam generator tubes (as anticipated). More testing would be desirable to quantify the reduction in fatigue life. However, at or below stress levels presently anticipated to occur, the attachment of gauges appears to have no significant effect on ongoing tube integrity. That is, the gauge attachment does not appear to lower the 10^7 endurance limit of the tubes to levels below expected in-service stresses.

Thus, based on these tentative results, it appears that the strain gauge attachment will likely have no significant negative impact on the structural integrity of the steam generator tubes for at least a two year period.

4.0 PREPARATION PROCEDURES FOR IN-SITU MEASUREMENTS

Although there are no plans now to initiate an in-plant steam generator tube stress/vibration measurement investigation, there may be a requirement for this at any time in the future. This section of the report is included to briefly indicate specific preparation procedures that would be required. It is emphasized that a period of up to three months or more might be needed to prepare for such in-plant measurements.

The major effort as to laboratory preparation requirements, centers on the acquisition, quality checking and calibration of the strain gauges themselves. Full details of exact requirements are contained in Appendix A. However, a brief list is below:

- i) Ordering of Strain Gauges - Delivery usually about 12 weeks
- ii) Quality Checking of Gauges - 3 weeks
- iii) Gauge Calibration - 4 weeks

Other efforts would also be required for in-plant work which are not covered in detail in this report. These efforts include:

- i) Development of procedures to attach strain gauges to tubes in the U-bend region. (Location of gauges to be determined on the basis of future failures.)
- ii) Flexible protective covering for strain gauge leadwires between tube and shroud.
- iii) Strain gauge leadwire routing through steam drum and pressure boundary penetration details.

In addition to these efforts, licensing and procedural details for all work at the station must be satisfied. Much of the

required preparation efforts can only efficiently be done after an inspection of the area.

5.0 RECOMMENDATIONS

The performance of this program has been in a situation of declining priority: significant tube failures have not occurred over the past few years. As such, a strong directive to conclude this work at this time has been given by the BNGS 'A' Steam Generator Tube Steering Committee.

With regard to the prediction of operating tube integrity due to gauge attachment, there are a number of points to be considered. These are:

1. Fatigue tests to determine the suitability of strain gauge measurements should be done at the levels of stress amplitude that the actual steam generator tubes experience. This can only be determined by actually performing in situ measurements, which is the object of the program itself. An alternative will be to perform significantly longer term fatigue tests and to more widely bracket a wide range of stress levels than has been done.
2. Long term tests of instrumented tubes under pressurized steam conditions have not been done. Chemical or metallurgical problems may only become apparent, for example, after six months of tests.

As such, it is recommended that long term testing of instrumented tubes be performed to ensure predictable behavior under fatigue and environmental conditions. It is suggested that continuous tests be performed for up to two years. Such testing if successful in demonstrating continuing integrity of instrumented tubes will not guarantee that no problem will occur, but it will add the highest degree of assurance that can be obtained by laboratory efforts.

6.0 CONCLUSIONS

This study investigated various salient concerns regarding the measurement of stress and vibration on operating steam generator tubes. Three major areas were covered: quasi-static strain measurement; vibration measurement; and the safety of the procedure regarding the continuing integrity of the instrumented tubes themselves.

Much of this work, including the calibration of the strain gauges and the fatigue testing of instrumented tube sections, involved new applications of technology which are significantly better than has been applied to previous steam generator tube measurement projects. (These new developments were the direct result of recent foreign investigations and developments or were the result of improvements made by Ontario Hydro on the basis of external experience in this area.) The major result of the project is the development of an effective in situ stress/vibration measurement capability for steam generator tubes.

On the basis of brief laboratory tests (in relation to conventional comprehensive fatigue and metallurgical tests), there exists a reasonable degree of likelihood that instrumented steam generator tube failure would not occur for a period of at least two years due to the strain gauge attachment.

There are several aspects of the measurement capability which remain to be fully verified by an actual in-plant pilot measurement project or by more extensive testing that is relevant to a two year time span. However, there is no reason at this time to believe that such an in-plant project would not be successful.

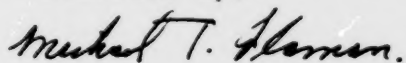
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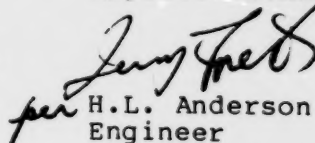
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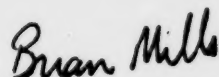
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APPENDIX A
CALIBRATION OF STRAIN GAUGES
FOR QUASI-STATIC STRESS MEASUREMENTS

Introduction

Typical steam generator tube environment consists of:

- (a) Steam generator tube pressure: 1450 psi
- (b) Steam generator pressure: 700 psi
- (c) Saturated steam at 260°C

Successful accurate quasi-static strain measurements in this environment depends on the ability to separate the temperature and pressure-induced strain from the measured strain to find the stress-induced strain. It is also important to know long term behaviour characteristics of the strain gauges in this environment, ie, time and temperature dependent drift.

This appendix describes the various tests performed and their results in the Experimental Stress Analysis Laboratory of Mechanical Research Department to determine the ability to measure quasi-static stress/strain changes on steam generator tubes.

DESCRIPTION OF TESTS

Test #1: Qualification test for the clamp calibration technique for apparent strain due to temperature for Ailtech brand resistance type weldable strain gauges.

Purpose

The purpose of this test was to determine the suitability of clamps to calibrate the strain gauges (for temperature effects) in the laboratory before attachment to the steam generator tubes.

Procedure

- (a) The gauge was installed in the I-600 clamping rig (as detailed in Figure A1). It was cycled between 100°C and 300°C for repeatability and then calibrated for apparent strain between room temperature and 300°C in 25°C steps.
- (b) The gauge was then installed on a 18" long steam generator tube using spot weld technique. This duplicates a field installation.
- (c) The first cycle apparent (due to temperature) strain data for the attached gauge was obtained.
- (d) The data obtained in procedures (a) and (c) were compared which, in effect, compares actual "field" results for apparent strain with predicted results (from prior calibration).

Results

The discrepancy between predicted and actual data does not exceed 20 $\mu\epsilon$, as shown in Table A1.

Conclusion

Apparent strain data obtained by using this clamping rig is in acceptable agreement with actual data.

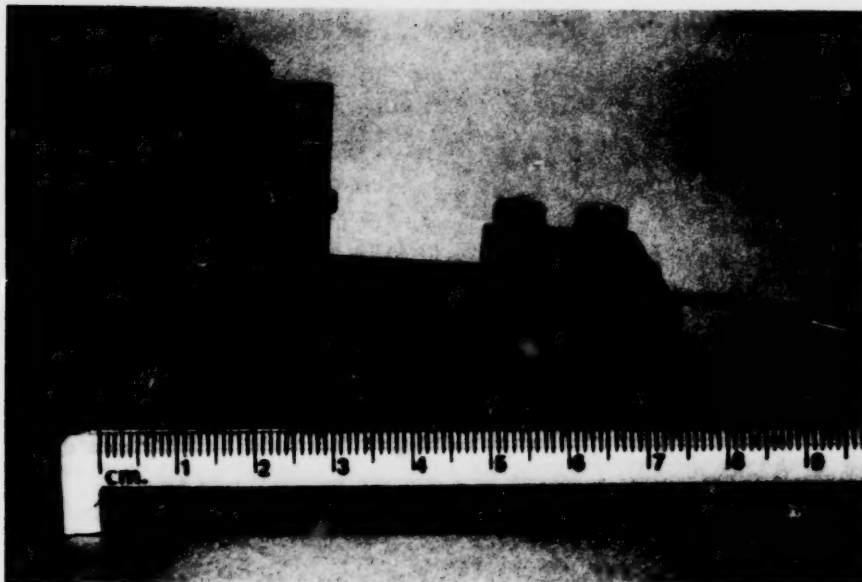
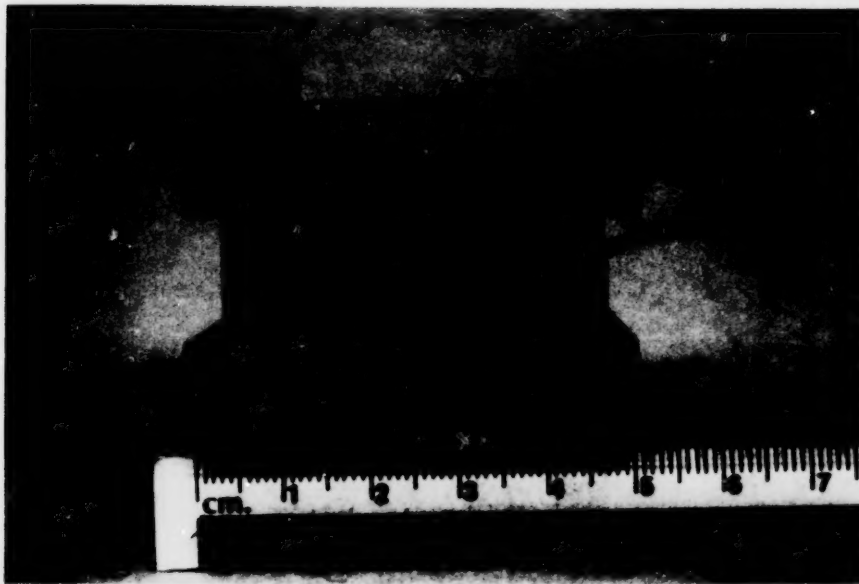


FIGURE A1
VIEWS OF STRAIN GAUGE CALIBRATION CLAMP

Comparison of Apparent Strain Values Obtained by Using Clamping Type Calibration Rig and After Spot Welding on a Steam Generator Tube. For Ailtech Strain Gauge Type: SG-425-001LHF (70)-80-INC600 S/No. 22767-13.

Apparent Strain By Using Clamping Type Calibration Rig		Apparent Strain After Spot Welding the Gauge to S.G. Tube (1st Cycle Data)	
Temp °C	Strain $\mu\epsilon$	Temp °C	Strain $\mu\epsilon$
21	00	21	00
54	+65		
75	+104		
101	+146	101	+150
126	+189	126	+193
150	+224	151	+231
175	+262	176	+269
200	+299	201	+305
226	+331	226	+337
251	+362	252	+371
276	+393	277	+406
301	+420	302	+436
20	-2	22	-2

Table A1

Test #2 Long term stability test for Ailtech brand resistance type weldable strain gauge in saturated steam at 300°C.

Purpose

The purpose of this test was to measure gauge reading drift under simulated steam generator conditions. Drift would be due to temperature or steam induced degradation.

Procedure

An eighteen inch long steam generator tube with Ailtech brand strain gauge installed on it was put in a small pressure vessel filled with saturated steam at 300°C and the gauge was monitored for 71 days on a daily basis.

Results

During 71 days of monitoring at 295°C and saturated steam conditions, the maximum strain fluctuation was +7 $\mu\epsilon$. When cooled down to room temperature, the gauge returned to -6 $\mu\epsilon$.

Conclusion

The results of this test indicate that slow changes in the strain reading (drift) and permanent offset (zero shift) due to simulated in situ steam generator conditions are well within acceptable limits.

Test #3 Determining apparent strain due to combined pressure and temperature effects on Ailtech brand research type strain gauges at simulated steam generator operating conditions.

Purpose

The objective of this test was to determine the apparent strain output of the Ailtech strain gauges due to pressure and combined pressure/temperature conditions.

Test Procedures and Results

1) Verification of Pressure Stability for Primary Side.

S.G. tube without pressure vessel was pressurized to ~1500 psi at room temperature and monitored for 3 weeks. Pressure dropped from 1500 psi to 1000 psi during first 15 hours and then maintained constant pressure for the remaining time. Pressure varied with room temperature during 24 hour cycle by 100-150 psi.

To overcome the above mentioned initial drop of 500 psi and daily fluctuation, 1 qt accumulator was installed in the circuit. Pressure was then monitored for 4 days. The pressure remained at initial set value for all 4 days with a daily fluctuation of ~10 psi.

The temperature was increased to ~300°C and the pressure was set to 1300 psi and monitored for a few days.

The pressure remained at 1300 psi with daily fluctuation of ~10 psi. This completed the verification of the ability to hold primary side pressure constant during subsequent tests.

2) Calibration of Apparent Strain for Due to Temperature Effects.

Calibration for apparent strain due to temperature was done three times and results are as shown in Table A2.

3) Calibration of Apparent Strain Due to Pressure Effects.

The pressure vessel was assembled. Flange bolts were torqued to 180 ft-lb. To determine the apparent strain due to pressure, the S.G. tube pressure and the vessel pressure

were increased simultaneously to 800 psi in steps of 100 psi. The strain gauge output was recorded for each step and are as shown in Table A3.

4) Final Verification Tests.

The steam generator tube was pressurized with water to 1450 psi. The vessel was partially filled with water and temperature was increased to 260 °C. The vessel pressure was built up to 670 psi due to vapour pressure. The output from the strain gauge as well as steam generator tube pressure, vessel pressure and vessel temperature were monitored for 72 days.

Comparison of Calibration Data for Apparent Strain Due to
Temperature Obtained at Different Times for Ailtech Gauge
S/No. 22767-13.

March 5, 1986 Clamped in I-600 Calibration Rig		March 18, 1986 First Calibration After Spotwelding Gauge to S.G. Tube		April 7, 1986 Second Calibration		July 10, 1986 Third Calibration	
Temp °C	Strain $\mu\epsilon$	Temp °C	Strain $\mu\epsilon$	Temp °C	Strain $\mu\epsilon$	Temp °C	Strain $\mu\epsilon$
21	00	21	00	21	00	23	00
54	+65			48	+55	48	+39
75	+104						
101	+146	101	+150	93	+132	91	+107
126	+189	126	+193				
150	+224	151	+231	142	+206	140	+175
175	+262	176	+269				
200	+299	201	+305	193	+277	189	+237
226	+331	226	+337				
251	+362	252	+371	242	+340	237	+293
276	+393	277	+406				
301	+420	302	+436	292	+400	289	+359
20	-2	22	-2	25	+11	224	+293
						177	+246
						136	+201
						93	+139
						51	+72
						32	+32
						22	+12

Table A2

Apparent Strain Due to Pressure Calibration

Vessel Pressure	S.G. Tube Pressure	Apparent Strain
psi	psi	$\mu\epsilon$
3	7	0
116	122	+5
245	247	+11
354	357	+16
416	418	+19
520	525	+24
640	645	+30
697	703	+33
792	798	+37
2	6	0

Table A3

Note Vessel pressure and steam generator pressure were kept the same so that the strain gauge does not see any strain due to physical deformation of the S.G. tube due to pressure difference.

Vessel pressure decreased significantly three times due to water loss in the vessel. Each time more water was pumped in the vessel and the vessel pressure returned to normal operating pressure.

Throughout this time, the strain gauge output was stable and compared well with calculated strain. Comparison of calculated strain with measured strain at different conditions are shown in Table A4. Details of the calculation are shown at the end of this appendix.

COMPARISON OF MEASURED AXIAL STRAIN WITH CALCULATED AXIAL STRAIN AT DIFFERENT
TIMES DURING LONG TERM MONITORING OF THE AILTECH STRAIN GAUGE IN SIMULATED
STEAM GENERATOR ENVIRONMENT

Date/ Time	Measured Axial Strain $\mu\epsilon$	S.G. Tube Pressure psi	Vessel Pressure psi	Vessel Temperature $^{\circ}\text{C}$	Apparent Strain Due To Temperature (1) $\mu\epsilon$	Apparent Strain Due To Pressure (2) $\mu\epsilon$	Strain Due To Pressure Induced Stress (3) $\mu\epsilon$	Calculated Axial Strain (4) $\mu\epsilon$
April 15/86 15:00	287	1461	283	183	236	13	30	277
April 17/86 04:00	372	1466	696	257	317	33	20	370
May 2/86 15:07	369	1481	671	257	317	32	21	370
May 2,/86 15:12	329	6	670	254	314	32	-17	329
July 3/86 09:00	363	1470	648	255	316	31	21	368
July 3/86 10:00	351	1474	0	255	316	0	37	353
July 3/86 11:13	316	0	0	256	316	0	0	316

Note: 1. From apparent strain due to temperature calibration data of July 10, 1986.

2. From apparent strain due to pressure calibration data.

3. Strain due to pressure induced stress = (S.G. Tube Pressure - Vessel Pressure) x 0.025418665*

4. Calculated axial strain = Apparent Strain Due to Temperature + Apparent Strain Due to Pressure + Strain Due to Pressure Induced Stress

*See Appendix A

Table A4

Details of Calculations

Calculation of Axial Strain due to pressure induced stress

Measured Parameters

Steam generator tube pressure: 1550 psi
Steam generator tube temperature: 20°C
Vessel pressure: 0 psi
Axial strain: 40 $\mu\epsilon$

Calculations

Where

P = Pressure
 r_i = Inside Radius
 r_o = Outside Radius
E = Young's modulus of Elasticity
 D_i = Inside Diameter
t = Wall Thickness

$$\begin{aligned}\text{Axial stress } \sigma_{\text{Axial}} &= \frac{F_{\text{Axial}}}{\text{Area}} = \frac{P \times \pi \times r_i^2}{\pi(r_o^2 - r_i^2)} \\ &= \frac{1550 \times .212^2}{.256^2 - .212^2} = 3383 \text{ psi}\end{aligned}$$

$$\text{Axial Strain } \epsilon_{\text{Axial}} = \frac{\sigma_{\text{Axial}}}{E} = \frac{3383}{29 \times 10^6} = 117 \mu\epsilon$$

$$\begin{aligned}\text{Hoop Stress } \sigma_{\text{Hoop}} &= \frac{F_{\text{Hoop}}}{\text{Area}} = \frac{P \times D_i}{2t} \\ &= \frac{1550 \times 0.424}{2 \times 0.044} = 7465 \text{ psi}\end{aligned}$$

$$\text{Hoop Strain } \epsilon_{\text{Hoop}} = \frac{\sigma_{\text{Hoop}}}{E} = \frac{7465}{29 \times 10^6} = 258 \mu\epsilon$$

Calculated Strain seen by the axial gauge = Axial Strain +
Poisson's Ratio x Hoop Strain

$$= 117 + (-0.3) \times 258 = 40 \mu\epsilon$$

Since all parameters except pressure are constant, one constant can be derived from above calculations such that it can be multiplied with any given pressure to give calculated value of strain due to pressure induced stress.

$$\text{Constant C} = \frac{\text{Calculated Value of Strain}}{\text{Pressure}} = \frac{40}{1550} = 0.025418665$$

Note: Apparent strain due to pressure can be defined in two ways.

First Method: A strain gauge is attached to a specimen; entire specimen is pressurized.

The signal from the gauge is considered to be " ϵ_p ".

Second Method: A strain gauge is attached to a specimen; entire assembly is pressurized.

The strain on the specimen due to pressure (stress) is subtracted from the the strain signal. Remaining value to considered to be " ϵ_p ".

If it is desired to measure stress changes due to all effects, the 2nd method is preferred.

If it is desired to measure stress "changes" due to "all effects", except stress in tube due to hydrostatic pressure, the 1st method can be used.

For this report the first method was used for stress on outer surface of steam generator tube wall due to internal pressure (P_i) and outer pressure (P_o).

$$\sigma_1 \text{ (axial)} = \text{Pi} \frac{b^2}{a^2 - b^2} - \frac{\text{Po} a^2}{a^2 - b^2} = 2.182595\text{Pi} - 3.182595 \text{ Po.}$$

$$\sigma_2 \text{ (hoop)} = \text{Pi} \frac{2 b^2}{a^2 - b^2} - \text{Po} \frac{(b^2 + a^2)}{a^2 - b^2} = 4.36519037\text{Pi} - 5.36519037 \text{ Po}$$

$$\sigma_3 = -\text{Po}$$

b = inner radius .212"

a = outer radius .256"

$$\begin{aligned} \text{Now } \epsilon_{AX} &= \frac{\sigma_1}{E} - \frac{\nu \sigma_2}{E} - \frac{\nu \sigma_3}{E} \\ &= \frac{2.1826 \text{ pi} - 3.1826 \text{ po} - \nu 4.36519 \text{ pi} + \nu 5.36519 \text{ po} + \nu \text{po}}{E} \end{aligned}$$

$$\nu = 0.3 = \frac{\text{Po}}{E} (-3.1826 + 6.36519\nu) + \frac{\text{Pi}}{E} (2.1826 - 4.36519)$$

$$E = 29$$

or if E = 28.5, $\nu = 0.29$

$$\epsilon_{AX} = 0.0321647 \text{ pi} - 0.0672525 \text{ Po}$$

For hydrostatic pressure where $\text{Po} = \text{Pi}$,

$$\sigma_1 = -p, \sigma_2 = -p, \sigma_3 = -p.$$

$$\text{and } \epsilon_{AX} = \frac{-p}{E} (1-2\nu).$$

$$\text{Now } \epsilon_S = \epsilon_R = -\epsilon_A = -\epsilon_p$$

(Strain due
to Stress)

(Measured
strain)

(Strain due to
temperature)

(Strain due
to pressure)

APPENDIX B
EVALUATION OF STRAIN GAUGES FOR VIBRATION/DISPLACEMENT MEASUREMENT

Following the failure of peripheral steam generator tubes at the U-bend supports, apparently due to low amplitude, high cycle fatigue, a program was initiated to study the feasibility of employing strain gauges on steam generator tubes for the evaluation of vibration displacement.

The objective of the vibration tests was to ascertain whether or not the output from the strain gauges at the support locations could be consistently correlated with measured tube displacement over a wide range of excitation levels and tube support conditions.

The results of tests on a six-span U-tube are documented in this appendix.

1. Description of the experimental rig and procedure

The evaluation of the gauges was carried out on a six-span mock-up of a peripheral Bruce U-Bend shown in the photograph in Figure B1.

The rig consists of a tube identical to the Bruce NGS 'A' boiler tubes bent to the 1.0 meter bend radius of the outer tubes in the steam generator. The rig simulates the support conditions from the last broached-hole support plate on the straight leg through the bend region with drilled plates forming the supports on the U-bend at the 40, 90 and 140 degree positions. A short straight length of the tube, approximately 0.63m, below each broached-hole support is held at the end in a drilled plate arrangement that permits variation of the tube/support clearance with two set-screws. The tube supports were held on the wall in channel brackets. The details of the U-bend supports, the broached-hole supports and the tube-end supports are shown in figures B2, B3 and B4 respectively.

Vibration excitation of the tubes was produced by an external LING shaker mounted on a support bracket independent of the tube configuration. The shaker was attached to the tube by a lightweight bracket shown in figure B5.

Tube response was monitored at 18 positions around the U-bend, as shown in figure B6, using the following transducers:

1. Strain Gauges: Two orthogonal gauges were located at each position support and mid-span; the gauges at the mid-span were used to study the change in strain with mode shape. In all, nine pairs of strain gauges were installed. The gauges were Micro-Measurement bondable gauges used in this feasibility study to reduce costs without compromising the results.

2. Accelerometers: Two lightweight B&K 4375 accelerometers were mounted on beeswax to monitor tube motion in the in-plane and out-of-plane directions at each monitoring location on the U-bend. Because of the ease of the beeswax mounting, which provides a high mounted resonance, the accelerometers could be moved to each measurement location in turn in order to reduce the number of accelerometers used.

3. Proximity probe: A proximity probe was used to monitor tube displacement in the out-of-plane direction at measurement locations as a control reference for the accelerometers. A lightweight aluminum plate was attached to tube parallel to the probe face at the measurement location to reduce the effects of tube curvature on the proximity probe.

The signal conditioning equipment associated with the transducers is shown in figure B6.

To determine the response frequencies of the U-bend configuration impact tests were performed and mode shapes determined.

The mode shapes are documented in figure B7. The lowest natural frequency was 45 Hz.

The shaker, located at the midspan position between the broached-hole support plate and the 40 degree support, location 3, was then used to excite the tube at the lowest natural frequency over a range of input voltages. Strain gauge response at the support and accelerometer response at the midspan were recorded for each U-bend span of the tube over the range of excitation tested.

One set of tests was performed with the tube jammed in its supports at the broached-hole support plate (location 1 & 2) and at the 40 degree support (locations 5 & 6). The purpose of this test was to simulate, as closely as possible, the behaviour of a single span tube.

The data were recorded on magnetic tape and on a U-V visicorder. Transfer functions of the stress measured at the support with its corresponding mid-span displacement were determined from the data.

2. Results and Discussion

The strain gauges provided consistently accurate frequency response data. However, no consistent correlation could be determined between the strain measured by a pair of gauges at a support and the corresponding mid-span displacement for the multi-span tube.

The only case in which a consistent correlation between the strain gauge output and the mid-span measurement could be obtained was the case with the tube jammed in its supports at the broached-hole support plate and at the first 40 degree U-bend support.

The results from this "single-span" test are documented in Table B1. For a wide range of excitation level the ratio of strain gauge output to mid-span displacement is constant at approximately 0.8 V/mm rms. This case represents an ideal condition in the sense with the tube is behaving as a single span tube with no clearance at the supports to introduce any non-linearities.

Similar results could not be achieved when the tube was not jammed at the supports. The results of two tests with nominal design clearances at the supports are documented in Table 2. These results are representative of the data taken in the program and show that no consistent ratio of strain gauge output to midspan displacement could be achieved. The data became increasingly erratic with the onset of impacting which is a nonlinear phenomenon. Again, in the case with the tube jammed at the supports, no impacting could occur.

Strain gauges have been used for tube vibration measurement in experimental work on flow induced phenomena/eg,1,2,3/. In the cases examined in references 1 and 2 the tubes were single span with nearly ideal support conditions. Under such conditions the calibration of the strain gauges at the support with the maximum displacement is straightforward since the tube will always respond with the same normalized mode shape without any nonlinear behaviour introduced at the supports. The response of the strain gauges will then have a linear relationship with the displacement which will vary only according to the fluid excitation.

In the case of a multi-span tube several frequencies and therefore mode shapes will contribute to the response. The modal contribution to the response will vary as the fluid loading varies. Tube response and strain will change as the tube support conditions change. Strain gauge response will then be difficult to correlate to tube displacement because the contribution of the various modes and the effect of changing support conditions (due, eg., to thermal effects) on the calibration will be indeterminate from the strain gauge data alone.

Reference 3 is a report on the use of strain gauges and accelerometers for flow-induced vibration analysis in the Three Mile Island once-through steam generator tubes. In the vibration measurement program on the steam generators there was an attempt to correlate the strain measured at the upper tubesheet to the displacement measured by accelerometers in the first span below the tubesheet.

The results of the program are similar to those produced here at Research Division; that is, it was found that the strain-to-displacement relationship changed with changes in the support conditions introduced by changes in temperature and excitation level and no consistent correlation factor could be determined.

3. Conclusion

The results of the test program indicate that the strain gauges can be used to obtain reliable frequency information; however, the support strain gauge output cannot be used to reliably estimate tube mid-span displacements because changes in the support conditions introduced by temperature and fluid excitation changes will affect the correlation in a manner that is indeterminate.

If displacement measurements are required in operating steam generators then in-tube biaxial accelerometer installation should be considered, or strain gauges installed at each desired measurement location.

References

1. W.J. Heilker, R.Q. Vincent, "Vibration in Nuclear Heat Exchangers due to Liquid and Two-Phase Flow", ASME Journal of Engineering for Power, Vol. 103, April 1981.
2. M.J. Pettigrew, J.H. Tromp, J. Mastorakos, "Vibration of Tube Bundles Subjected to Two-Phase Cross-Flow", ASME Journal of Pressure Vessel Technology, Vol. 107, Nov 1985.
3. The Babcock & Wilcox Company, "Flow-induced Vibration Analysis of Three Mile Island Unit-2 Once-Through Steam Generator Tubes, Volume 1", E.P.R.I. Report NP-1876, June 1981.

SG1 Output* vs Midspan Displacement at Location 3 for the
Case with Tube Jammed at Support Locations 1&2 and 5&6

Shaker Input volts peak at 45 Hz	Strain Gauge output/ midspan displacement
1.0	0.79
0.75	0.80
0.5	0.80
0.25	0.81

Table B1

Ratio of Strain Gauge Output to Corresponding Midspan
Displacement for Multi-Span Tube

Shaker Input volts rms at 45 Hz	S65 Output*/ midspan displ. V/mm rms	S69 Output*/ midspan displ. V/mm rms
0.4	0.33	0.61
0.3	0.27	0.77
0.2	0.18	0.85
0.15	0.16	0.88

Table B2

* - all strain gauge data were normalized to the same gain.



FIGURE B1
SIX-SPAN EXPERIMENTAL BRUCE U-BEND RIG

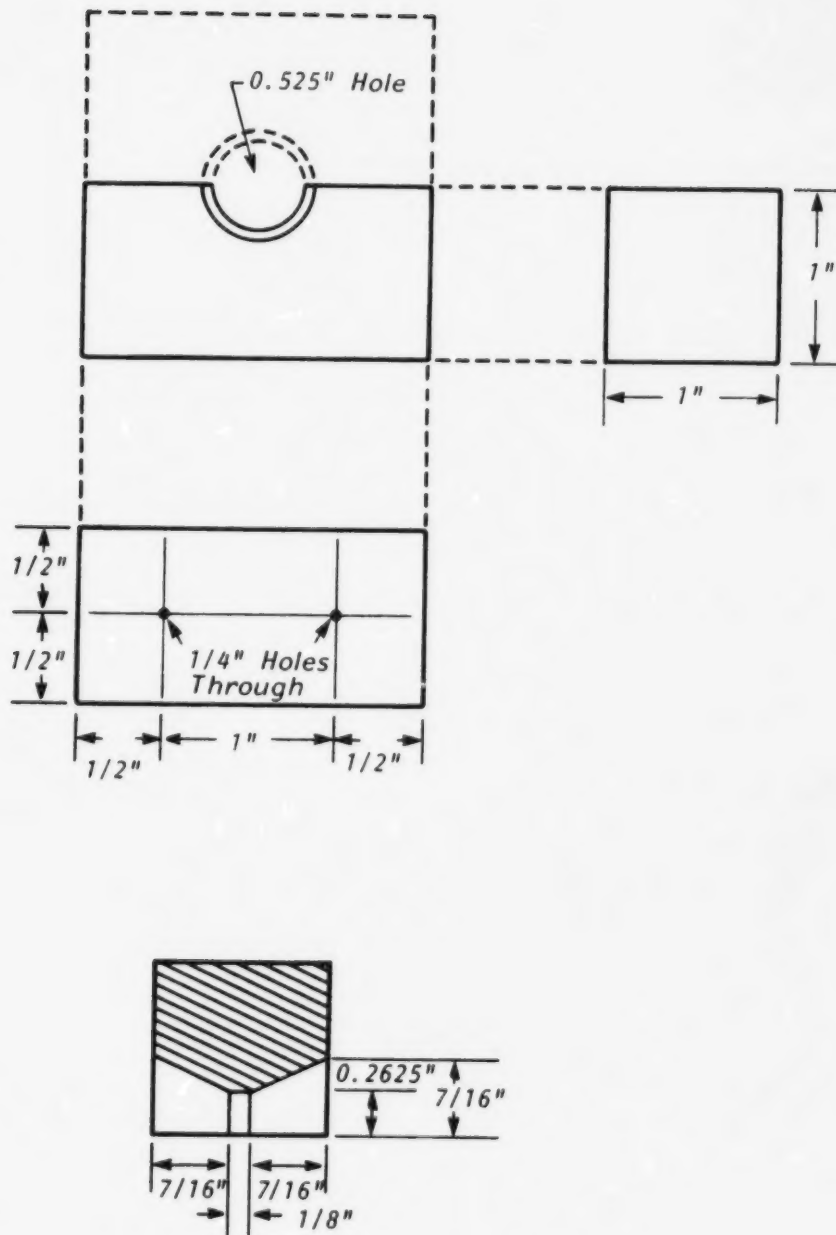


FIGURE B2 (a)
90° U-BEND SUPPORT

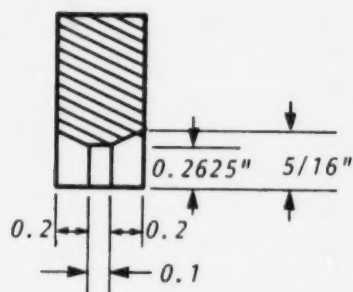
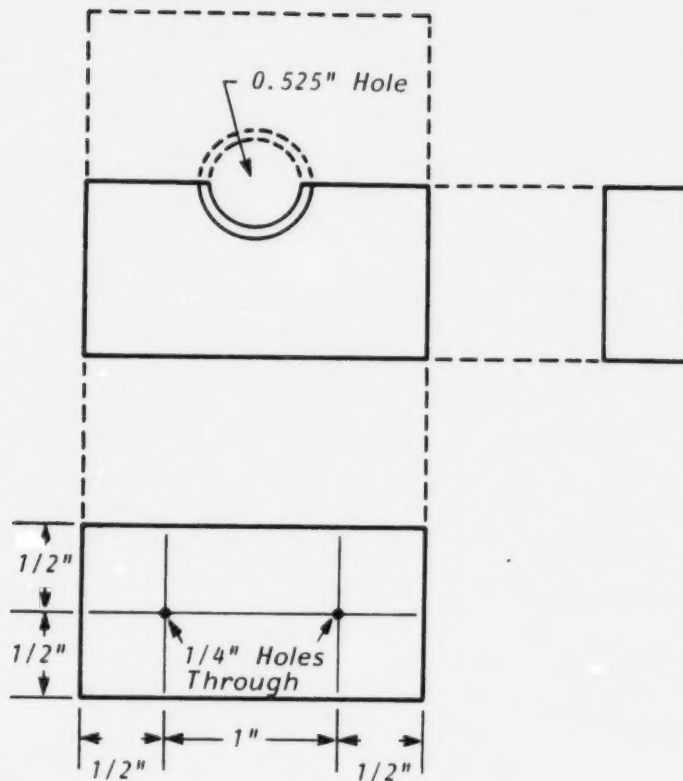


FIGURE B2(b)
40° AND 140° U-BEND SUPPORT
(all Dimensions in Inches)

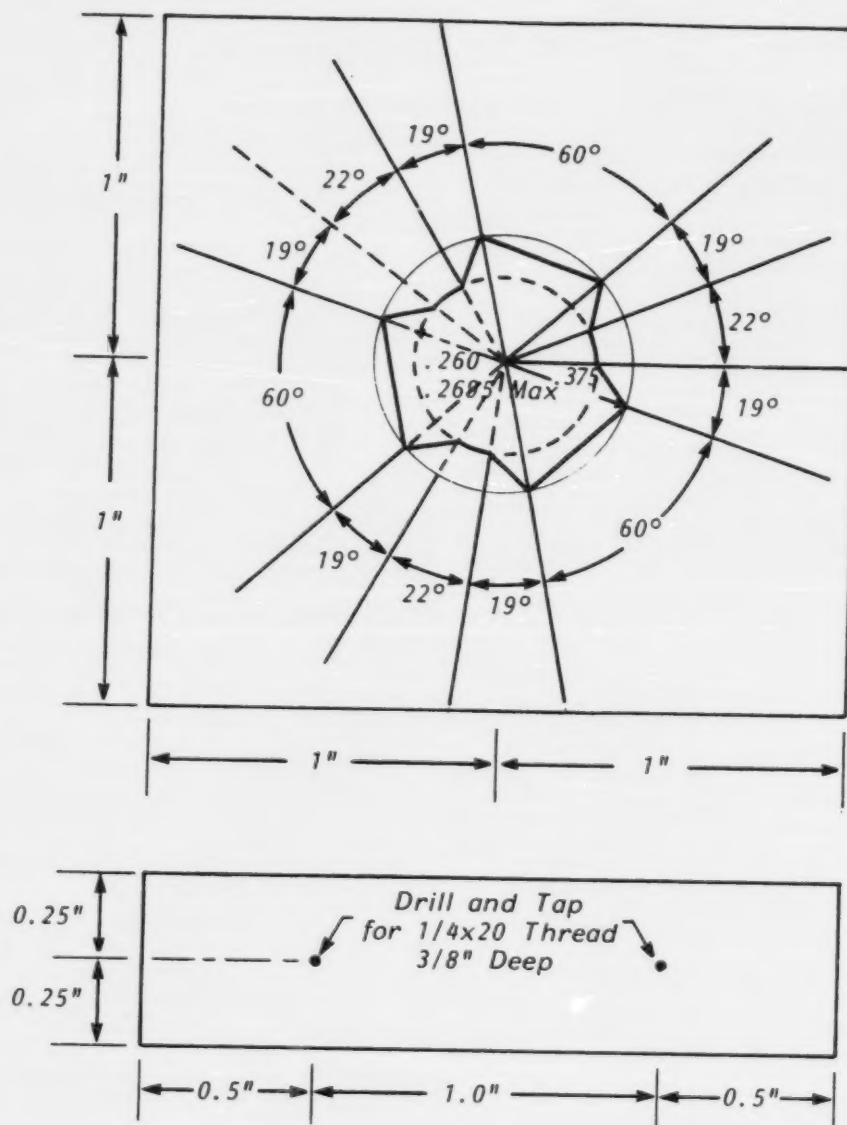


FIGURE B3
BROACHED-HOLE SUPPORT
(all Dimensions in Inches)

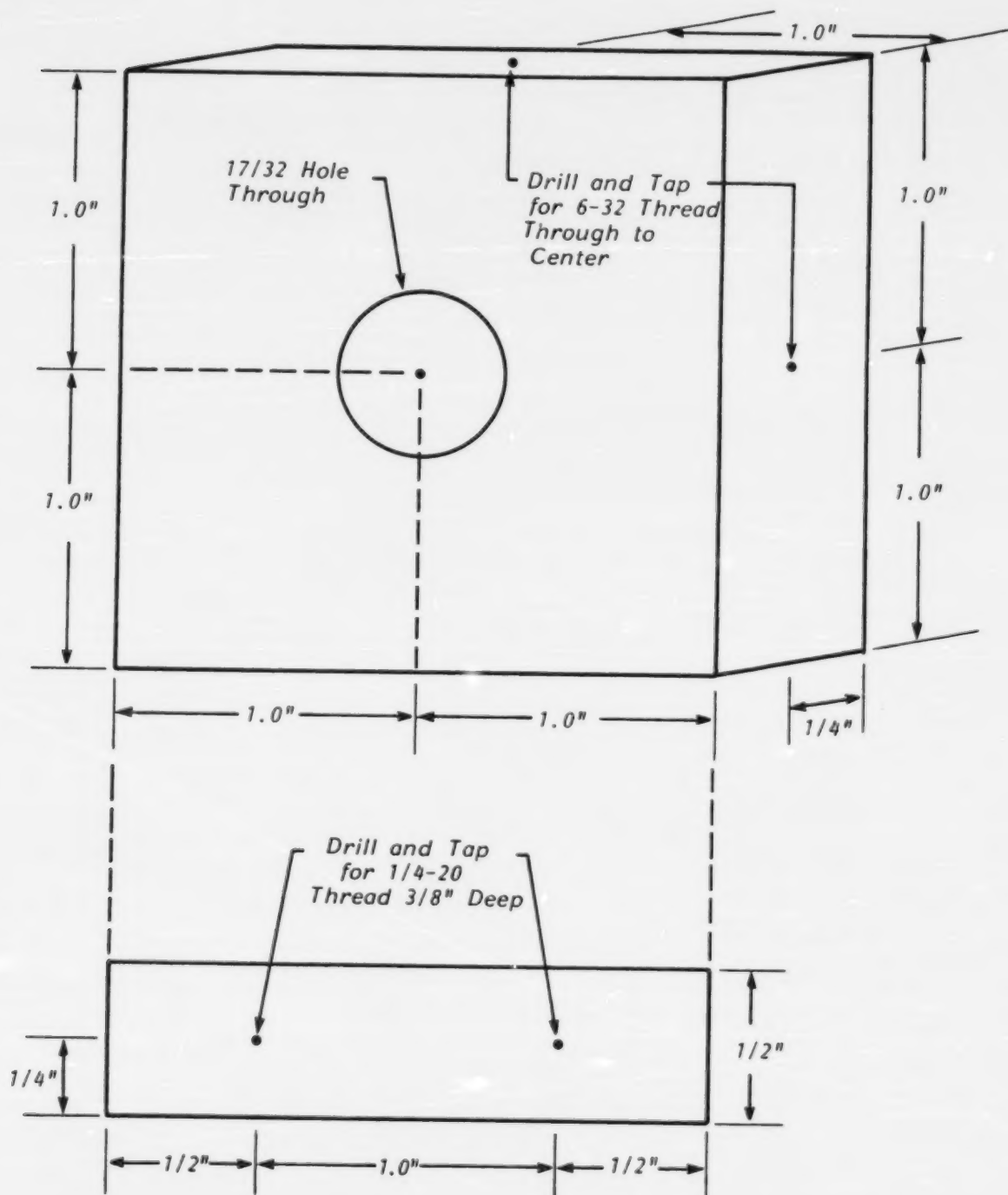


FIGURE B4
TUBE-END SUPPORT
(all Dimensions in Inches)

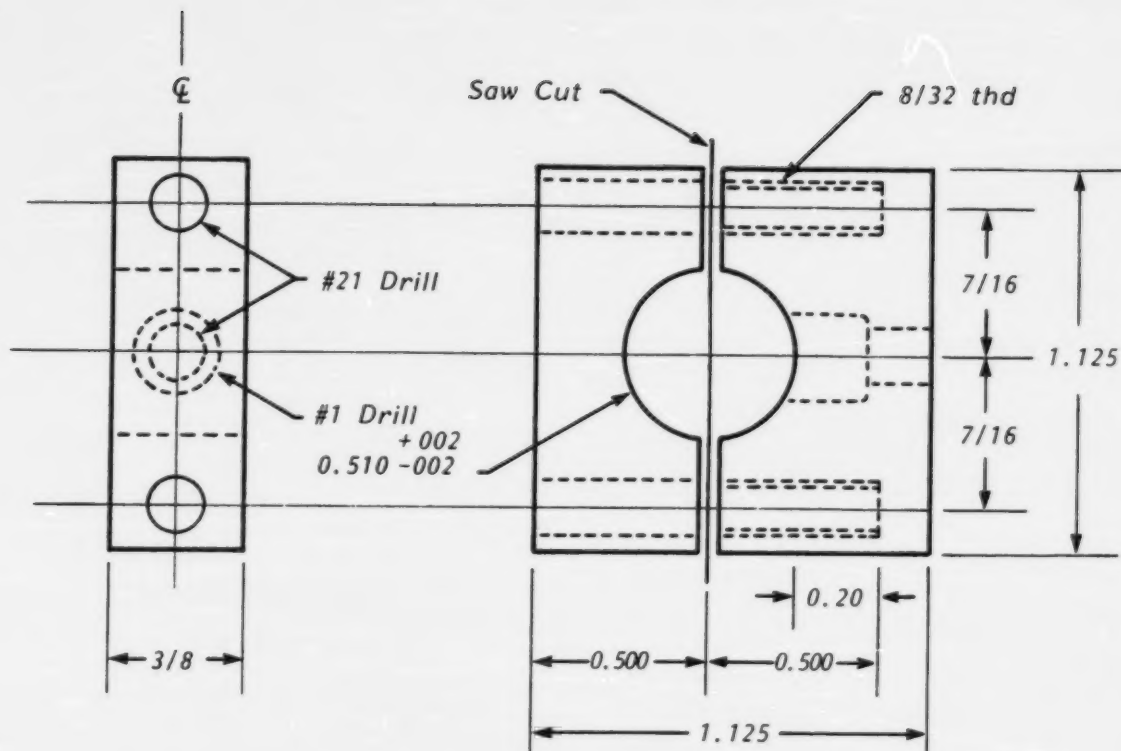


FIGURE B5
TUBE CLAMP FOR SHAKER ATTACHMENT
(all Dimensions in Inches)

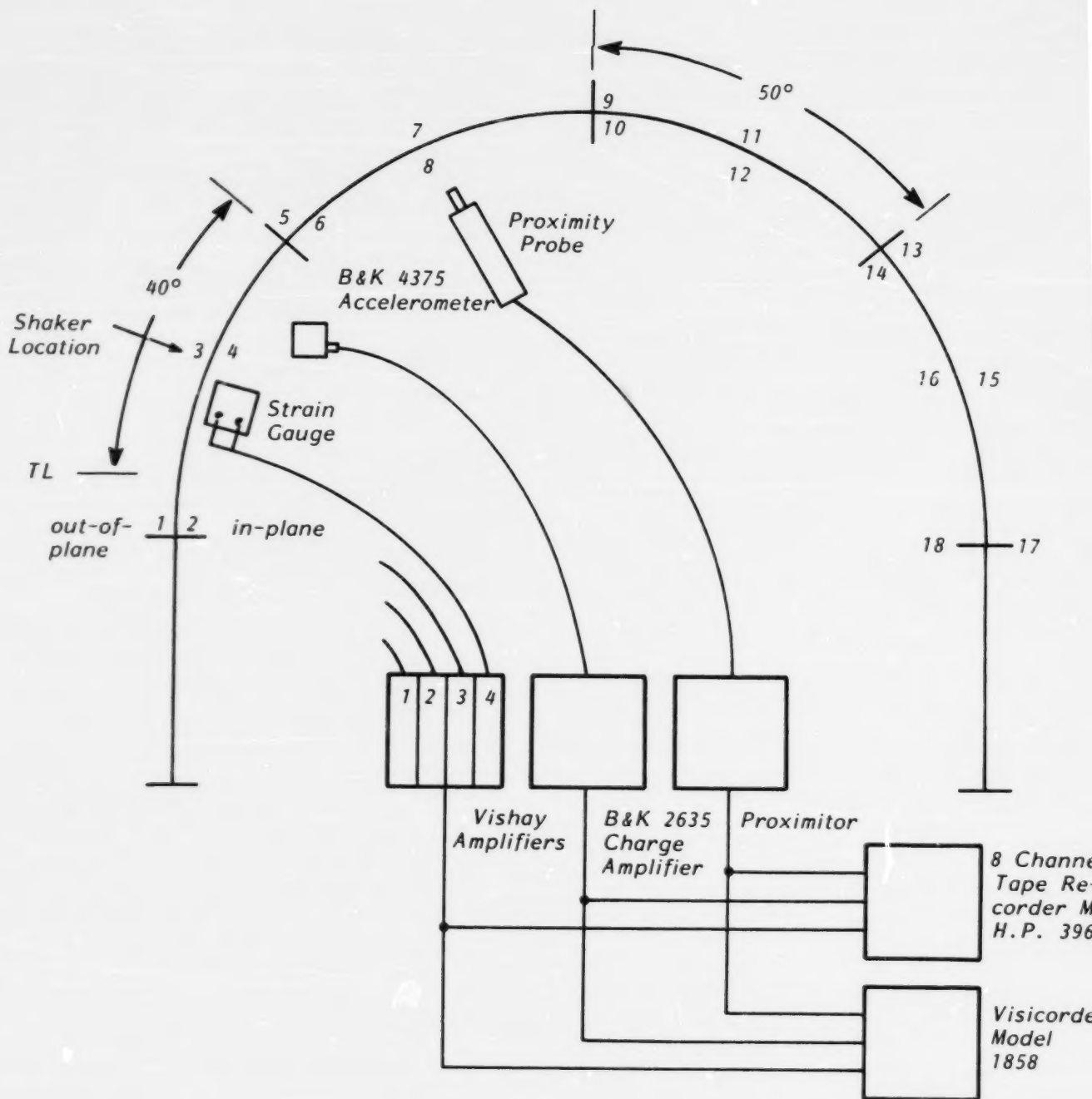


FIGURE B6
MEASUREMENT LOCATIONS
& EQUIPMENT SET-UP

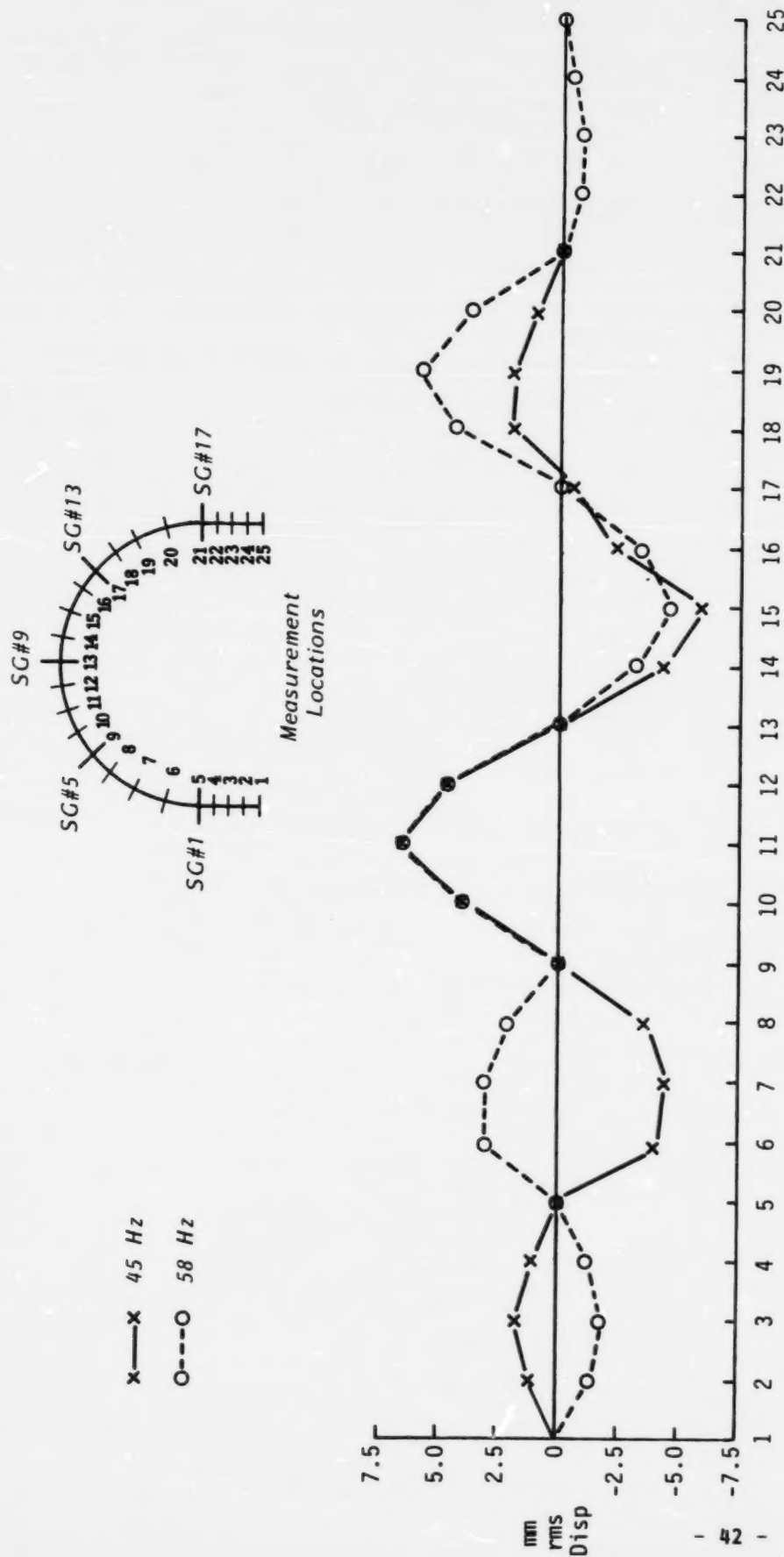


FIGURE B7
MODAL ANALYSIS OF U-BEND RIG

APPENDIX C
THE DEVELOPMENT OF A FATIGUE TESTING MACHINE
FOR STEAM GENERATOR TUBES AND FATIGUE TESTING RESULTS

Introduction

One of the major concerns involved in attempting to instrument steam generator tubes in situ is the effect of the instrumentation itself on the tubes. There are two separate issues; the first is the effect of the instrumentation on the measurements, i.e. will the instrumented tubes behave differently than non-instrumented tubes. This concern is addressed in Appendix B. The second issue, and the one to be addressed in this appendix, is the effect of the instrumentation on the life expectancy, or fatigue life, of the steam generator tubes.

The sensor to be applied to the steam generator tubes is the Eaton ('Ailtech') strain gauge. A photograph is shown in Fig. C1. These gauges are usable over a wide range of temperatures and environmental conditions. They are hermetically sealed to the high temperature leadwire, which enables them to be used underwater or in a steam environment. The gauges to be used inside the steam generator have been custom made for Ontario Hydro from Inconel 600 for compatibility with the steam generator tubes. A portable resistance spot welder (Fig. C2) is used to attach the gauge to the structure to be instrumented.

The principle of operation of the gauge is straightforward. Strain in the structure is transmitted through the spot welds to the central cylindrical strain sensing tube. Inside this tube is a strain sensitive wire surrounded by a densely packed insulating powder (magnesium oxide). The strain compresses or elongates the wire which results in a resistance change proportional to the strain.

There are two ways the gauge could adversely affect steam generator tube life. First, the strain gauge produces a reinforcing effect on the (thin-walled) tube and this geometric discontinuity may adversely affect tube integrity. Second, the introduction of the gauge spot welds may also cause premature tube failure due to metallurgical or stress concentration effects.

This fatigue testing program was initiated in order to address these concerns.

Previous Work

Babcock & Wilcox and Combustion Engineering have both investigated the effects of weldable strain gauges on steam generator

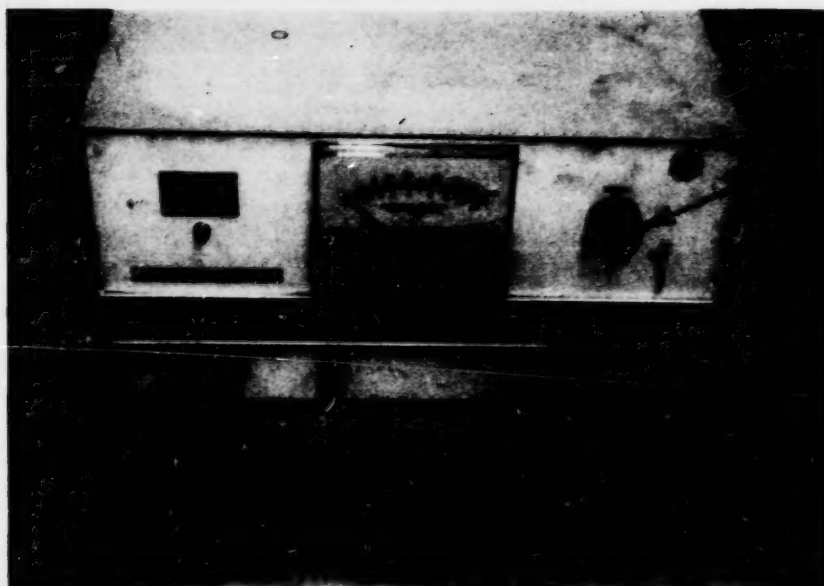
High -
Temperature,
Leadwire



Strain
Tube

Welding
Flange

FIGURE C1
WELDABLE STRAIN GAGE



Weld
Energy
Control

Ground
Connection

Welding Tip

FIGURE C2
PORTABLE RESISTANCE SPOT
WELDER USED TO ATTACH STRAIN GAGES

tubes/1,2/. However, their results were somewhat inconclusive. In addition, their results can only be directly applied to specific US steam generator tubes. Ontario Hydro's steam generator tubes are, in some cases, heavier walled than US tubes, and the design of our steam generators is somewhat different. Another problem with the US test data is that C-E performed their fatigue tests on artificially wall-thinned tubes (in order to use a standard four-point bending test machine). Thus, their test samples deviate from the in-plant situation significantly. Therefore, this work, while forming a useful basis for comparison, was considered not sufficient to adequately address the tube integrity concerns.

Fatigue Testing Approach

1. Choice of specimen

The American Society for Testing Materials (ASTM) has established uniform requirements for the fatigue testing of materials/3,4/. For any materials fatigue tests to be generally acceptable, these guidelines should be followed. Specimens for these standard material fatigue tests are to be machined from solid coupons of the bulk material. The standard tests are not intended to determine the fatigue life of manufactured components, but rather to determine a baseline material fatigue curve for conservative design.

In our case, the fatigue life of bulk Inconel 600 would certainly differ significantly from the fatigue life of an actual steam generator tube sample. More importantly, extrapolating the tube fatigue life from the material fatigue life is possible but difficult. There are many factors which affect the fatigue life of a steam generator tube versus the material from which it is made, some of which are poorly quantified. Therefore, it was decided that actual, unaltered steam generator tube samples must be tested, since the objective of the testing was to compare strain gauged tubes to a control group of ungauged tubes.

The length of the tube sample to be tested was also quite important. In the ASTM materials tests, the material sample is usually quite small. However, in order to simulate in-plant conditions as closely as possible, it was decided to use a 69 in. long sample for testing. This closely corresponds to the distance between support plates in Bruce NGS "A" steam generators. A long tube sample also lowered the mean stress condition in the test sample, as described in the next section.

2. Design of Fatigue Test Machine

There are many ways to perform a fatigue test on a specimen. Ref. 5 gives an excellent overview of this subject. In general,

when testing of manufactured components is required, the configuration of the test specimen has a powerful influence on the testing options.

In this case, it was required to test a long, slender, axisymmetric tube. Applying direct tension/compression loading in a hydraulic materials test machine was one possible approach, but was rejected for two reasons. First, such test equipment is very expensive and not readily available. Second, this type of machine is severely limited in its testing frequency; 1 Hz is not uncommon as an upper limit. This would have required prohibitive amounts of test time to reach the standard 10,000,000 to 100,000,000 cycles.

Thus, a high speed test method was sought. One of the oldest techniques for high speed fatigue testing is the rotating bending test. In this test method, a sample of the material to be tested is clamped in the test machine, which then applies a four point bending load to the specimen. The specimen is then rotated in the loaded (bent) configuration. This produces an alternating stress which goes through a complete cycle once every revolution. Speeds up to 10,000 RPM and loads up to 8,000,000 in.lb have been achieved/5/. This test method is, in general, designed to test the fatigue life of materials, not components.

The ASTM has defined the configuration of the test specimen in a standard rotating bending test. Details can be found in Ref. 5, but the important thing to note about these samples is that they are narrowed in the center section in order to ensure failure there. This is because, in four point bending, the bending moment is uniform between the inner loading points (at which there must be bearings or physical supports of some kind). Without any center area weakening, the specimens would always fail at the inner loading points since these loading points will always constitute a stress concentration.

In order, therefore, to use a standard rotating bending test for our steam generator tubes, it would appear that the central section of the tube must have thinned walls. (This is the approach taken by Combustion Engineering.) However, there are two problems with this approach. The first is a practical one. To further thin a 0.0445 in. thick wall uniformly, accurately, reliably, and without weakening the tube to the point that ovalization and buckling become a problem is quite difficult. More importantly, if the center section is weakened, the test is no longer on a steam generator tube as it is in the field.

Since we desired to test significant lengths of unaltered steam generator tubes, a four point loading approach was not possible.

Therefore, an alternative was sought to a conventional four point loading rotating bending fatigue machine.

Several alternative designs were considered. The final concept chosen was based on loading the tube as a pin-ended column. Similar machines are used for fatigue testing rods/5/. When the buckling load is reached, the tube deforms into a half-sine shape. Any desired stress amplitude can then be achieved by controlling the center point deflection of the tube. The loaded tube is then spun about its central (curved) axis to generate the alternating stress.

The test machine built to implement this concept is shown in Fig. C3. The motor drives a main shaft, which in turn drives both ends of the tube sample in order to avoid torsion in the sample. The intermediate bearings which can be seen in the figure apply no load to the tube; they act as supports for dampers to control horizontal vibration during startup of the machine, and are removed at full speed. A non-contact (optical) counter records the number of cycles applied to the tube. A dial gauge (not shown) is used to adjust the center point deflection of the tube, thus setting the stress amplitude for the test. This adjustment is accomplished by moving one end of the tube towards the other using a screw mechanism, which is then locked in position. Several calibrations for stress versus center point deflection were performed using a strain gauged tube sample.

It should be noted that the mean stress in the tube is not zero, as it would be in a four point bending machine. This is due to the axial load required to buckle the tube, which is always present. However, this axial (compressive) stress is only 1700 psi, which is quite small relative to the stress amplitudes applied during testing. (Also, internal pressurization due to heating of a water-filled tube or due to other measures could reduce or eliminate this compressive stress).

3. Test Description and Results

Since the tests are comparative, i.e. comparing the fatigue life of strain gauged tubes to non strain gauged tubes, the simplest test conditions have been used in order to speed up development and testing. These conditions are room temperature and water filled (but depressurized) tubes. The test machines have ovens included as part of their design, and tests at temperature and pressure similar to in service conditions can also be run.

Since the actual weldable strain gauges to be used in the field are quite expensive, they have been simulated by small pieces of Inconel 600 shim stock of the same size as the base flange of the strain gauges. These coupons of I600 are spot welded onto the tube the same way an actual gauge would be.

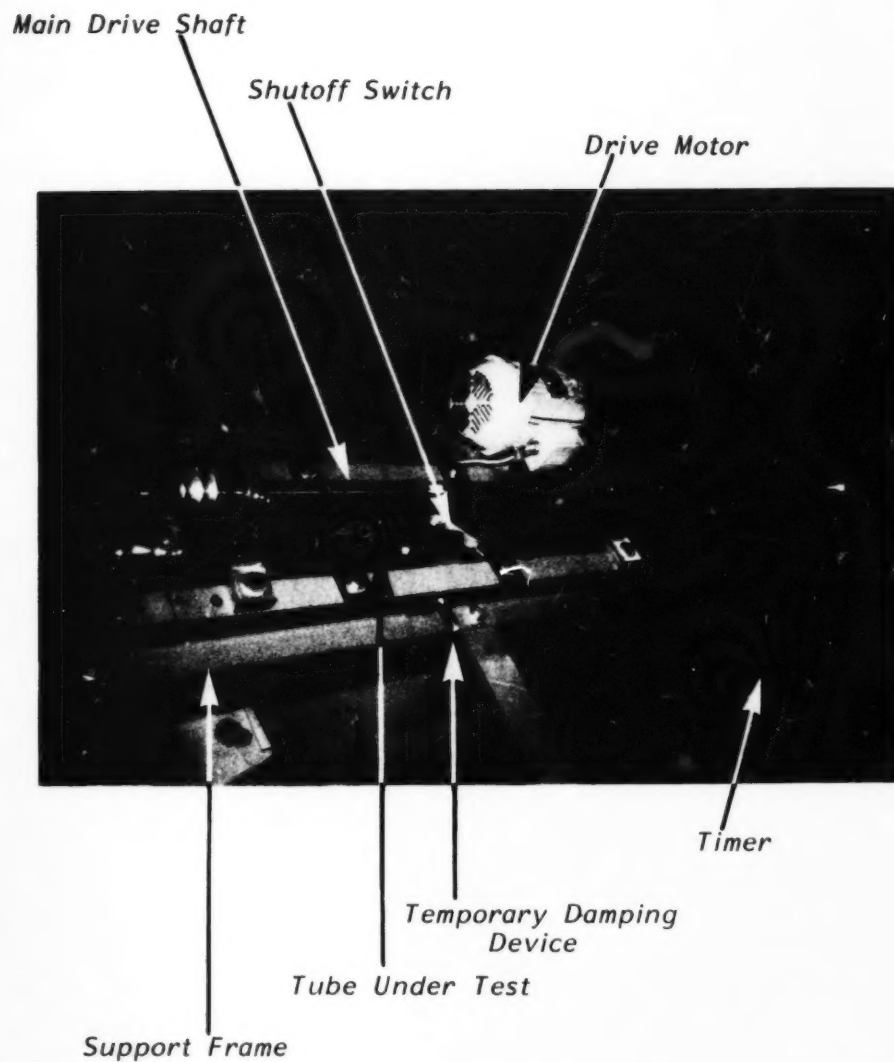


FIGURE C3
PROTOTYPE FATIGUE TEST MACHINE
FOR TESTING STEAM GENERATOR TUBES

The tests which have so far been conducted indicate several things. First, all of the tubes have failed in the central section i.e. the central one-third of the tube. None of the tubes have failed at the end supports. This indicates that the problems with sample failure at the quarter point supports, which have plagued four point loading machines, are eliminated by this test machine design. In addition, failures at or near the centre indicate that the machine itself is behaving as designed.

There have been two tubes which have failed at a relatively low number of cycles, i.e much lower than expected. In both these cases, a mechanical defect such as a scratch could be seen at the fracture. This emphasizes the need to avoid any such physical damage to in-service tubes during the gauge installation.

Ten tubes have been tested with simulated strain gauges attached. Three of these were tested at relatively high stress amplitudes, i.e. near the endurance limit of the tubes (which is approximately a zero-to-peak stress amplitude of 20,000 psi). In each case, the tube fractured at the end of the simulated strain gauge. This is to be expected, since the spot welds, no matter how carefully applied, do act as stress concentrations. In addition, the strain gauge coupon acts as a geometric discontinuity and would probably initiate failure no matter how it was attached to the tube (eg adhesive bonding).

Five tube samples with simulated strain gauges attached have been tested at stress amplitudes of less than 10,000 psi, which is much lower than the endurance limit. This stress amplitude has been chosen to simulate the maximum anticipated service stresses in the field. These tubes all reached over 20 million cycles (one tube was tested to over 110 million cycles) without failure, at which time the tests were stopped.

These tests indicate that there is a reduction in the 10^7 endurance limit of the tubes due to the gauge attachment. However, at or below the anticipated maximum in-service alternating stress, the effect appears negligible, ie, should not cause premature tube failure.

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